

Chapter 8

Power Systems

Providing the required power is an open problem in mobile robotics, and in the case of space robotics things are no better. Experimental robots often receive the energy required for moving and performing their tasks through an umbilical cord, but this is not possible in the case of operational devices. There are some exceptions in the case of low mobility rovers, whose goal is the exploration of a very small area around the landing site that may receive their energy from the lander. While this is possible, even if not very advisable, for short term operations, to operate in this way for a long time poses reliability and mobility problems that cannot be solved.

Another possibility is to power the moving machine through a microwave beam. Energy may be transferred in this way from a fixed power generation plant to a moving machine, but the drawbacks are many. Firstly the technology is not yet fully available. Moreover, energy can be transmitted in this way only in a straight line, so that the range of the moving machine may be extremely reduced in the case of small bodies, where the horizon is close, and above all on rough terrain. Finally, the very intense microwave beam may pose severe problems of electromagnetic compatibility with other communication or electronic devices. Perhaps the only application may be that of working machines for building roads and civil engineering structures or for surface mining, particularly on airless worlds.

Generally speaking, the vehicle or the robot must have on board its own energy source.

When choosing the power source for any particular application two parameters are of paramount importance: its *energy density* (in J/kg, or often in Wh/kg) and its *power density* (in W/kg).

Power sources are usually said to be *power limited* or *energy limited* depending on whether the most severe limitation comes from the power density or the energy density.

The energy density of some energy sources and accumulators is reported in Fig. 8.1, where the performance of nuclear (fission) and chemical energy storage are compared with those of some electrochemical accumulators.

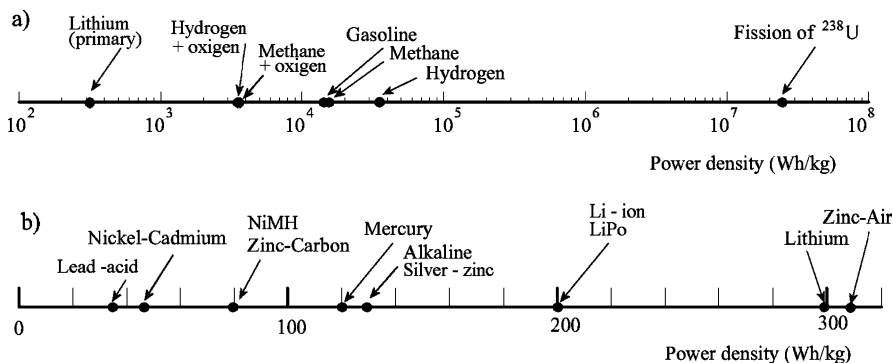


Fig. 8.1 (a) Energy density of some energy sources and accumulators in Wh/kg (logarithmic scale). (b) Expanded zone where the electrochemical accumulators are located (average values, linear scale)

8.1 Solar Energy

8.1.1 Photovoltaic Generators

One of the most common power sources in space applications are photovoltaic generators. They are the typical power limited source, in the sense that they have a somewhat low power density, but a virtually infinite energy density since they get their energy directly from the Sun, a source almost without any limitation, on the scale we are interested in. Actually they too have an energy limitation since their duration is limited and then the energy they can produce in their useful life is limited.

Since the efficiency of solar cells is rather low, only a small part of the energy from the Sun is converted into electric energy, the remainder being reflected or transformed into heat, which in space must be dissipated by radiating it away. While the efficiency of the early cells was only a few percent, research devices have achieved an efficiency of 42% and the goal is at present to reach an efficiency of 50%. The efficiency of some types of solar cells is summarized in Table 8.1.

The cost of cells varies widely, the advanced types being much more costly than the conventional ones. Generally speaking, the efficiency of cells operating in space is lower than that of cells operating on Earth, an effect that is compensated by the higher energy received by the cells owing to the lack of screening due to the atmosphere.

Solar cells are assembled to form panels, usually flat, extensible appendages of the spacecraft, but sometimes the cells are directly mounted onto its outer surface. In the case of robots working on the surface of a planet, the panels may be mounted flat on the top of the robot's body, like on the rovers used on Mars, or may be mounted in such a way that they can be kept oriented toward the Sun.

In the former case a further reduction of the power produced with the cosine of the angle between the normal to the surface and the direction of the Sun is present.

Table 8.1 Efficiency of various types of photovoltaic cells

Type	Efficiency
Amorphous silicon	6%
Multicrystalline silicon	14–19%
Single junction gallium arsenide	25%
Multi-junction gallium arsenide	40%
Best research cells up-to-date	42.7%

Table 8.2 Values of the solar radiation flux in W/m^2 in space at the distance from the Sun of the planets when at their perihelion and aphelion

Planet	Perihelion	Aphelion
Mercury	14,446	6,272
Venus	2,647	2,576
Earth	1,413	1,321
Mars	715	492
Jupiter	55.8	45.9
Saturn	16.7	13.4
Uranus	4.04	3.39
Neptune	1.54	1.47

The efficiency of the cells decays in time, due to spontaneous decay and to damage from radiation and impacts of micrometeoroids and space debris or, on planetary surfaces, due to dust accumulation. A greater number of cells than that strictly needed must be available, so that enough power is still generated after some of them have been put out of use.

At the average distance of Earth from the Sun (1 Astronomical Unit), the *solar constant*, i.e. the power of the electromagnetic radiation from the Sun, is almost 1.4 kW/m^2 ; with an efficiency of 18% the power per unit surface of the panel perpendicular to the Sun's direction is thus 250 W/m^2 . It is difficult to state the power density of a space photovoltaic generator since its mass depends on many constructional details. Often quoted values span from 80 to 150 W/kg , with the possibility of going beyond 200 W/kg in the near future.

The available power varies with the square of the distance from the Sun. At Mars orbit, then, the power density is about half than at Earth orbit, although being quite variable along the Mars year, since the orbit of that planet is quite elliptical. At the distance from the Sun of Venus or of Mercury (Table 8.2) the power collected by solar cells is much higher. However, getting close to the Sun the solar panels work at higher temperatures and their efficiency decreases.

Another cause of reduction of the power density of solar cells is the presence of an atmosphere that absorbs partially the energy from the Sun. This may be due to the atmospheric gases or to the dust carried by the atmosphere. In particular, in the case of Mars, accumulation of dust on the panels reduces the power output of solar

generators. With some luck, the panels may be cleaned from time to time by wind, as happened with the *Spirit* and *Opportunity* rovers.

The solar panels of the MERs have a total deployed area of 1.3 m^2 and were made of three-layer cells: gallium indium phosphorus, gallium arsenide and germanium, whose effective efficiency is between 23 and 25%. At the beginning of the mission the panels could produce about 900 Wh during one Martian sol (24 h, 39 min, 35 s), used to keep two lithium-ion batteries located inside the warm electronics box charged. After 90 sols of work the energy produced dropped to 600 Wh per sol, due to both season change and performance degradation.

The use of solar cells beyond the orbit of Mars is questionable, and certainly other power sources are needed at these distances from the Sun.

While large solar panels can be used in space, and even on the surface of planets in the case of fixed installation, to use large panels on a moving vehicle or robot is questionable, if not in the case of very slow machines requiring little energy and moving with limited accelerations.

To reduce the size of the photovoltaic panels it is possible to use mirrors to concentrate sunlight on smaller panels. This practice can be particularly expedient at distances from the Sun larger than that of Earth, but one of the main advantages of solar photovoltaic generation, namely its simplicity, is lost. Two surfaces, a concentrator plus a photovoltaic array are needed, although the latter is smaller than that of a non-concentrating system. The two surfaces must be controlled in such a way that the second remains in the focus of the first, while it tracks the sun in its motion. Particularly in the case of space applications, it seems that if a concentrating plant is used, it is more convenient to use a thermal generator than a photovoltaic one.

Example 8.1 A 2 m^2 solar panel having an efficiency of 22% lies horizontally on the Moon at the equator. Compute the maximum power supplied by the panel, the average power and the total energy supplied during a lunar day in which the sun passes at the zenith at noon.

The solar constant at the average distance of the Earth–Moon system from the Sun is $W_s = 1,367 \text{ W/m}^2$. The maximum power produced by the panel is 602 W.

The lunar day is 29 days, 12 h, 44 min, 3 s, i.e. 2,551,443 s long. If θ is the angle between the direction of the Sun and the horizontal, the power that the panel produces at a generic instant is

$$W = \eta S W_s \sin(\theta) = \eta S W_s \sin(\Omega_m t),$$

where S is the surface of the panel and Ω_m is the angular velocity of the apparent motion of the Sun on the lunar surface.

The total energy produced in a day is

$$E = \int_0^{T/2} W dt = \frac{\eta S W_s}{\Omega_m} \int_0^\pi \sin(\theta) d\theta,$$

where $T = 2\pi/\Omega_m$ is the duration of the day.

Performing the integration, it follows that

$$E = \frac{\eta S W_s T}{\pi} = 4.885 \times 10^8 \text{ J} = 135.7 \text{ kWh.}$$

The average power during the daylight hours is thus $\overline{W} = 383 \text{ W}$.

Note that this computation is only a first approximation evaluation since the efficiency of the solar cells cannot be considered a constant with such a large variation of illumination.

8.1.2 Solar-Thermal Generators

While in the case of small plants photovoltaic arrays have several advantages, in large plants solar thermal system may be more expedient. In solar-thermal systems the energy is produced by a thermal engine, for instance a steam turbine, operated by the heat from the sun. Mirrors are used to concentrate the light of the Sun onto a boiler, so that high enough temperatures can be reached. The advantages are those of a higher efficiency, which is, however, always limited by thermodynamic considerations, and the possibility of building large and lightweight mirrors in space.

As will be seen when dealing with nuclear reactors, in space it is not easy to use thermal energy in an efficient way, and this strongly limits the possibility of using solar thermal devices for power generation in space. A similar consideration holds also for the Moon and even Mars.

The mirror must anyway be controlled so that the boiler remains always in its focus and the complexity of the solar thermal systems is larger than that of photovoltaic systems. As a consequence, there is little advantage in using such a more complex system over panels of solar cells, at least for small and medium size spacecraft, while it may be so in case of large solar power stations on the surface of the Moon or of a planet. The optimum configuration depends upon the application and the power that has to be generated.

8.2 Nuclear Power

At present, there are two possible alternatives for nuclear power generation in space: radioisotope generators and fission nuclear reactors.

Extensive use of nuclear devices, both for propulsion and power generation on spacecraft and in planetary outposts and bases is essential for space exploration. Even on the Moon surface, where there is plenty of energy from the Sun and there is no atmosphere reducing the efficiency of solar energy system, only nuclear systems can guarantee survival through the long and cold nights, particularly for systems that cannot be hibernated but must remain operational for all the time.

In the past many concerns about safety of nuclear devices in space were forwarded. The fears of using radioisotope thermoelectric generators (RTGs) have been

greatly exaggerated, as is demonstrated by the few accidents involving nuclear powered spacecraft to date. The first occurred when the *Transit 5B-N3* satellite failed to attain its orbit in 1964. At that time the generators were designed to disintegrate in the high atmosphere, and the SNAP-9A RTG did so. No measurable excess radioactivity was found. The second accident occurred when the launch of the *Nimbus B1* satellite failed in 1968. The SNAP 19 generator was this time designed to remain intact and was recovered after 5 months in the ocean without any failure. Finally, when the lunar module *Aquarius* of the ill-fated *Apollo 13* mission disintegrated in the Earth's atmosphere, its RTG went down intact into the ocean without any measurable radioactive contamination being found. The same happened when the launch of the Mars 96 probe failed. The worst accident, and the only one in which there was contamination, occurred when the Russian *Cosmos 954* disintegrated in the atmosphere over an unpopulated region of northern Canada. Its large nuclear reactor (not an RTG, but a fully fledged reactor) disintegrated, and various radioactive fragments were found on the ground. The decontamination operation costing about 8 million dollars was paid for by the Soviet government. Subsequent Cosmos satellites had the provision for jettisoning the reactor, which was put in a safe higher orbit, before re-entry.

At any rate, these concerns caused a decrease of the funding for research in nuclear energy utilization in space: only thirty years ago it was taken for granted that by the end of the twentieth century large space stations powered by nuclear reactors could be built. The United States built several reactors of the SNAP (System Nuclear Auxiliary Power) class, but at present the largest space nuclear reactors are the Russian Topaz. A revival of the research in nuclear generator for planetary outposts and bases is a real need: only an extensive use of nuclear power can allow us to develop a spacefaring civilization.

8.2.1 Fission Reactors

As shown in Fig. 8.1, fission nuclear power has the highest energy density of all the energy source presently available.¹ The power density does not depend on the source in itself, i.e. on the nuclear fuel, but on the mass of the reactor and of the power conversion device.

The reactor generates thermal energy that has to be converted into a form that can be used to perform the required work, usually electric energy. In space efficient energy conversion is difficult, mainly because the efficiency depends on the temperature the heat is dissipated away from the conversion plant. Power plant operating on Earth use large quantities of coolant (usually water) to keep this temperature low, but in space no coolant is available.

¹When nuclear fusion reactions will be controlled an even more powerful source will be available and this will have dramatic consequences on all aspects of space exploration.

Heat must be exhausted by radiating it into space, but the quantity of heat that can be radiated away from a given surface depends on the 4th power of the temperature, a thing that compels to either use large radiators or to exhaust heat at fairly high temperatures. The value of the temperature that maximizes the performance of the plant in terms of power density is much higher than the temperatures used in power plants on Earth, leading to a much lower efficiency.

Technological advances in high temperature materials allowing to raise the highest temperature of the thermodynamic cycle may improve the situation, but generation of large quantities of energy in space, even with nuclear power plants, requires large and heavy power stations.

The situation on the surface of the Moon or of planets like Mars is surely better, but not much, since there is at any rate no cooling fluid. If the permafrost on Mars can be used as a heat sink, at the same time obtaining liquid water, the situation will certainly improve, but the technology is still to be developed.

At any rate, nuclear reactors may be used to power an outpost and to recharge the batteries or to produce fuel for vehicles and robots, but it is unlikely they will directly power them. The technology to build small and compact nuclear reactors is still to be developed, even if they are not inconceivable, and surely they will not be available in a foreseeable future.

8.2.2 Radioisotope Generators

When a compact and above all long lasting energy source is needed in space, radioisotope thermoelectric generators (RTGs) are a good alternative, based on well consolidated technology. They are small capsules containing a radioactive material such as plutonium-238, surrounded by a number of thermoelectric generators and then, on the outside, by a radiator. Owing to radioactive decay, the radioisotope reaches a temperature higher than that of the radiator and this difference of temperature makes a current to flow in the thermoelectric material. The efficiency of such devices is low, but they are compact, reliable and long lasting.

In the past RTGs were a very convenient—and necessary—power source for space probes exploring the outer solar system, like the Cassini probe. The generators on-board the Voyager probes allowed them to send to Earth information from beyond the orbit of Pluto after almost 40 years in space.

The drawbacks of Radioisotope generators are being weakly radioactive (they cannot be used in close proximity of a human crew or need shielding) and having quite a low power density. So they are more suited for robots operating in space than robots on a planetary surface and need to be shielded when used in people-carrying vehicles.

The radioisotopes to be used in generators must release much energy as radiation that can be easily absorbed and transformed into heat. In this respect alpha decay is much better than beta or gamma decay. It requires also a lighter shielding. The radioactive material also produces a significant amount of neutrons. Its half-life

should be long enough to produce a substantial amount of energy for the whole duration of the mission. Half-life must be chosen carefully, because radionuclides with a long half-life have a low energy release.

The best candidates are plutonium-238, curium-242 and -244, americium-241, strontium-90 and polonium-210, but there are other nuclides that could possibly be used. Plutonium-238 has the lowest shielding requirements (less than 2.5 mm of lead) and a long half-life (87.7 years). In many instances the casing itself supplies enough shielding and no specifically designed shield is required. It is usually employed in the form of plutonium oxide, PuO_2 .

All RTGs used in space were fueled by plutonium-238, while some units built for Earth applications used strontium-90 that has a shorter half-life, lower power density and much higher gamma radiation but has a lower cost. Plutonium is a strategically sensitive material and the scarcity of the supplies of plutonium may soon become a problem, making it difficult to power probes for deep space exploration.

For short durations polonium-210 has a very high power density, but an half-life of only 138 days: it has been used in some prototype RTGs.

Curium-242 and -244 produce gamma radiation and neutrons and thus require heavy shielding.

Americium-241 is a potential candidate isotope with a half-life of 432 years, longer than that of plutonium-238, but its power density is about 1/4 of that of plutonium and requires a heavier shielding: 18 mm of lead. The last figure is not so bad, since the americium is second only to plutonium in these respects. Its main advantage is availability, since it is widely used in smoke detectors, and may be an answer to the difficulty of procurement of plutonium. It is considered by ESA in case they decide to build RTGs.

Radioisotopes produce essentially heat, which must be converted in some form of usable energy, mainly electric energy. The alternatives studied in the past are essentially four in number: thermoelectric, thermionic and thermo-photovoltaic direct conversion and the use of dynamic generators using some sort of thermal engine.

The radioisotope generators used in space in the past are all thermoelectric generators, mostly owing to the simplicity and reliability of this architecture. However, the conversion efficiency is very low, usually between 3 and 7% in the various applications. The thermoelectric materials used include silicon germanium alloys, lead Telluride and Tellurides of antimony, germanium and silver.

Not only thermoelectric conversion has a low efficiency, but also thermoelectric material degrade in time and their efficiency decreases. For instance, the total power generated by the 3 RTGs of the *Voyager 1* and 2 probes in 2001 was reduced to 315 and 319 W from the original 480 W. Since the decay of the radioisotope in the 23 years of the mission accounts for a decrease of 16.6%, a decay of about 20% of the performance of the converter must be postulated.

A list of some plutonium-238 fueled RTGs used by NASA (28 US space missions using one or more RTGs were flown since 1961) is reported in Table 8.3.

The efficiency of thermionic converters is better than that of thermoelectric converters, being of the order of 10 to 20%. However, such devices require higher temperatures than those achievable in usual radioisotope generators. Generators fueled

Table 8.3 Main characteristics (electric power P_{el} , thermal power P_{th} , fuel mass m_f and total mass m) of some plutonium-238 fueled RTGs used by NASA

Model	Spacecraft	P_{el} (w)	P_{th} (w)	m_f (kg)	m (kg)
GPHS-RTG	Cassini, New Horizons, Galileo, Ulysses	300	4,400	9	60
MHW-RTG	LES-8 and 9, Voyager 1 and 2	160	2,400	4.8	37.7
SNAP-3B	Transit-4A	2.7	52.5	0.12	2.1
SNAP-9A	Transit 5BN1 and 2	25	525	1.23	12.3
SNAP-19	Nimbus-3, Pioneer 10, Pioneer 11	40.3	525	1.23	13.6
SNAP-19 mod.	Viking 1 and 2	42.7	525	1.23	15.2
SNAP-27	Apollo 12 to 17 ALSEP	73	1,480	3.8	20

by polonium-210 and some nuclear reactors designed for space applications had thermionic converters.

Thermo-photovoltaic converter are based on photovoltaic cells working in the infrared radiation generated by an hot body, namely the radioisotope capsule. Their efficiency is higher than that of thermoelectric converters: 20% efficiency have been demonstrated and 30% is a target. Combined converters, in which a first thermo-photovoltaic stage is followed by a thermoelectric second stage, allow a further increase in the efficiency.

A much higher efficiency, theoretically above 40%, can be obtained by dynamic energy conversion. Theoretically any thermal engine may be used, like a steam turbine or reciprocating engine working with the steam produced by the radioisotope or a hot air engine. One of the best choices, for what the efficiency is concerned, is a Stirling free piston engine connected with a linear electric generator. A prototype of a Stirling Radioisotope Generator (SRG) of this kind was developed by NASA and DOE: it demonstrated an efficiency of 23%, i.e. more than 3 times that of a conventional RTG. It is fueled by plutonium-238 and produces about 116 W electrical (about 500 W thermal) with 1 kg of plutonium and has a mass of about 34 kg. Its specific power at the beginning of the mission is 3.4 W/kg. The high and low temperatures of the thermodynamic cycle are 650 and 120°C, respectively. Even if for now SRGs have a specific power comparable with that of RTGs, they produce much less heat, requiring a smaller radiator and being less bulky.

The greater efficiency, with the subsequent lower mass and bulk for a given power output, is obtained at the cost of increased complexity of the system. However, some tests did show that a good reliability and a long operating life can be achieved even in the presence of moving parts. Also dynamic problems can be satisfactorily solved: SRGs, or other dynamic radioisotope generators, are thus a viable choice, particularly for the larger units.

Greater efficiency can be achieved by increasing the temperature ratio between the hot and cold ends of the generator. From this viewpoint, applications on the surface of a body with an atmosphere or in general applications where a cooling fluid is available, particularly if such fluid is cold, may have a higher efficiency than applications in space.

8.2.3 Radioisotope Heating Units (RHUs)

Similar to RTGs, but even less dangerous since they are far smaller, are Radioisotope Heat Generators (RHG) or Radioisotope Heating Units (RHU). These are tiny radioisotope capsules, usually of plutonium-238 contained in a platinum–rhodium alloy cladding, heating some crucial parts of a spacecraft that would otherwise have a too low temperature for correct operation. The mass of the radioisotope is just a few grams, while the total mass of the capsule may be about 40 g.

Radioisotope heaters make thermal control of spacecraft easier, since they allow to dispense with many electric heater, reducing the power requirements. They are particularly useful for probes traveling far from the Sun and rovers traveling on Mars, and even more in colder places like Titan. They are also essential on the lunar surface, if the device must remain operational during the long and cold lunar night, or even on the surface of planets like Mercury, where in spite of the very hot days, nights are extremely cold.

The *Cassini-Huygens* spacecraft at Saturn contains 82 RHUs (in addition to three main RTGs for power generation). RHUs and some electric heaters are usually located in a Warm Electronic Box (WEB) where temperature sensitive electronics and other components are located so that their temperature is controlled.

8.3 Chemical Power (Combustion)

Chemical energy stored in a fuel-oxidant combination has a high energy density and a power density that may be extremely high, depending on specific power of the conversion device. At any rate, the energy density is lower in space or on a planet with non oxidizing atmosphere than on Earth, since both fuel and oxidizer must be carried on board. If the device must work for a time that is not very short, provisions for refueling must be considered.

The combustion reaction commonly occurs between hydrogen and oxygen or between carbon and oxygen. The most energetic reaction is the one involving hydrogen, which can be stored in the form of molecular hydrogen or as more complex molecules containing both hydrogen and carbon (hydrocarbons) and often other elements. For storage, it is more expedient to store the fuel in liquid than in gas form, a thing that decreases the size and mass of the tanks.

Hydrogen in gas form has a very low density (0.0899 kg/m^3 at ambient Earth temperature and pressure) and to store it efficiently it must be kept at high pressure in suitable tanks. For instance, in some automotive applications, pressurized bottles maintaining a pressure 700 times atmospheric pressure have been used. In this condition, however, the mass of the tank is much higher than the mass of the gas it contains. At present, the target is to build tanks containing a mass of hydrogen equal to 6.5% the mass of the full tank, and even these estimates may be overoptimistic. The ratio between the hydrogen mass and the total volume of the tank is of the order of 70.6 kg/m^3 .

In liquid form, hydrogen has a boil-off temperature of 20.6 K at atmospheric pressure. In these conditions its density is only 71 kg/m^3 , 14 times lower than water density. A cryogenic tank is required for most applications and the boil-off rate must be considered when accounting for energy losses. Active boil-off control is a possibility, but even this requires energy.

Remark 8.1 Storage in pressurized tanks yields an apparent density that is close to that of liquid hydrogen, with no boil-off problems, even if the mass energy density is much lower when the mass of the tank is accounted for.

Another alternative is to store hydrogen in form of metal hydrides, like MgH_2 , NaAlH_4 , LiNH_2 , NaBH_4 , etc. They are either liquid or solid and have a good energy density by volume but their energy density by mass is often lower than that of hydrocarbons. Hydrogen may be tightly linked in the hydrides, requiring a non-negligible energy to free it.

Methane is a gas on Earth surface; its density is 0.717 kg/m^3 at 0°C . Its boiling point at atmospheric pressure is 112 K (-162°C) and its density in liquid form is 415 kg/m^3 . It is much easier to contain and store than hydrogen.

The next hydrocarbons, like ethane, propane and butane are still in gas form in Earth conditions and, except for their higher density and lower energy density, are similar to methane.

Heavier hydrocarbons are liquid. Usual liquid fuels are mixtures of different liquid hydrocarbons, with densities around $650\text{--}750 \text{ kg/m}^3$. They are easily contained in lightweight tanks, even if at the higher temperature experienced on the lunar surface they may have some boil-off.

If fuels based on hydrogen and oxygen are used in a place where the oxidant is not readily available, the simplest solution is carrying oxygen on board. The problem here is not dissimilar to the problem posed by hydrogen, since it is a cryogenic liquid (the boiling temperature at atmospheric pressure is 90.18 K or -183°C), although its density is much larger ($1,141 \text{ kg/m}^3$), thus requiring a much smaller tank.

To avoid the need of using cryogenic oxidizers, it is possible to use nitric acid (HNO_3) or hydrogen peroxide (H_2O_2) or other oxidizers. However, while there is a good experience in using such dangerous liquids as rocket propellants, they have seldom (or never) been used in thermal engines.

In case of short missions, like the *Gemini*, *Apollo* and *Space Shuttle* missions, which use fuel cells for electric power generation, the hydrogen–oxygen fuel–oxidant combination is carried directly from Earth, stored on board for the whole mission. For long missions chemical energy can be used as an intermediate energy storage: vehicles to be used on the Moon or other bodies may work on chemical energy, being refueled at an outpost where fuel is produced using energy from solar or nuclear power plant.

To power vehicles or robots there are two possibilities: using fuel cells that convert directly the chemical energy into electric energy or using some sort of thermal engine to obtain mechanical power.

8.3.1 Thermal Engines

Vehicles for planetary exploration may use more or less standard internal combustion engines, running on different fuel-oxidizer pairs, produced on site. Internal combustion engines have a somewhat low efficiency, in the range of 15 to 40%, but can have a high power density and benefit from a well established technology. The adaptations to work on hydrogen, methane or methanol are straightforward, and the relevant technology is available. Internal combustion engines come in sizes from less than 1 kW to several hundred kW and are cheap and reliable.

The drawbacks that may eventually lead to quit their use on Earth are less severe on other planets: since they will work in a closed cycle, recovering their exhaust to produce new fuel, pollution is not a problem and their low efficiency may not be a major problem if the fuel is produced using electricity from nuclear reactors, with the consequent availability of large quantities of energy.

This option has been discussed in detail in Sect. 7.3.3.

8.3.2 Fuel Cells

Fuel cells have a long history of space application, since they were developed for the *Gemini* missions.

In fuel cells the reaction between the fuel and the oxidizer is not a combustion process producing heat that is later converted into mechanical or electric energy, but an electrochemical reaction, similar to that occurring in batteries, producing directly electric energy. For this reason, the efficiency of fuel cells can be much higher than that of devices based on thermal engines.

The basic reaction occurring in fuel cells is that between hydrogen, which is separated into positive hydrogen ions and electrons at the anode, thanks to the presence of a catalyst, and oxygen, which is ionized negatively at the cathode and then migrates through an electrolyte separating the electrodes.

The catalyst, the electrolyte and the membrane separating the electrode may be of different types, and consequently different types of fuel cells, each one with its peculiar advantages and drawbacks for the different applications, exist.

- Alkaline fuel cells (AFC). Use a liquid, corrosive, electrolyte and must be fueled by pure hydrogen and oxygen, since impurities in the fuel poison the cell. Their efficiency is about 50%, or somewhat higher. They are used in space applications since when they were developed for the *Gemini* missions, their building and operating cost is fairly low and they do not require complex ancillary equipment, but are somewhat bulky.
- Proton exchange membrane fuel cells (PEMFC). Use a polymer electrolyte and require pure hydrogen as fuel. Contaminants like sulfur compounds and carbon monoxide poison the cell. Owing to their compact design and high energy density they are suited for automotive or robotic use, but require complex and costly

equipment, like compressors and pumps, that use about 30% of the energy produced. That notwithstanding their efficiency is around 30%. They operate at low temperature, about 80°C.

- Molten carbonate fuel cells (MCFC). Use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix. They are tolerant of the impurities in the fuel and can run on carbon monoxide. Thus they accept different hydrocarbons, like natural gas, that can be converted to hydrogen and carbon oxides or gases made from coal. They operate at high temperatures (650°C), which reduce their useful life. The efficiency is about 60%, but can be increased up to 85% if the waste heat is reused.
- Phosphoric acid fuel cells (PAFC). Use liquid phosphoric acid as electrolyte. They are not affected by carbon monoxide impurities in the fuel. Their operating temperature is 150 to 200°C. Their efficiency is low (37 to 42%), but can be increased if the waste heat is reused. They have a limited service life and use a costly catalyst.
- Solid oxide fuel cells (SOFC). Use a solid oxide material as electrolyte. They are not affected by poisoning from carbon monoxide and do not need high-cost, platinum-based, catalyst, but are affected by poisoning due to sulfur impurities. The operating temperature is quite high, from 500 to 1,000°C. Owing to the high temperature, they can use methane, or butane or even liquid fuels that are externally reformed. Their efficiency can reach 60%, and can be used for cogeneration of electric power and heat.
- Direct methanol fuel cells (DMFC). They are similar to PEMFC, but use directly methanol as a fuel. Their operating temperature is in the range of 50–120°C, but their efficiency is low, about 20%.

If oxygen–hydrogen fuel cells are used, the reaction product is water, which can be stored and carried back to the outpost, where is again converted into oxygen and hydrogen by an electrolyzer. This combination of fuel cell and electrolyzer is usually referred to as a regenerative fuel cell, and in practice works as a rechargeable battery. No material is consumed (except for some losses) and the system needs only energy.

When also methane or other hydrocarbons are used, also carbon dioxide is produced, together with water.

On Mars, oxygen and methane can be produced from the atmospheric carbon dioxide, using energy and some hydrogen from water from the permafrost of the planet. The carbon dioxide can then be exhausted to the atmosphere and the water can be recovered.

Hydrogen–oxygen alkaline fuel cells for space use are a mature technology and need no specific research. Much research is at present devoted to fuel cells for vehicular application, both for reducing their cost and for using different types of fuel. The choice of the fuel is quite limited: an interesting alternative to hydrogen is methane, which is much easier to store. If the lower energy density is not a problem, methanol or formic acid can be used as liquid fuel. The oxidizer is usually at any rate oxygen. The alternative of storing on board methane or methanol and then dissociate it chemically to produce the hydrogen to be introduced into the cell has the

disadvantage of causing the poisoning of most common types of cells, if impurities caused by the chemical process to obtain the hydrogen remain in the fuel.

Some applications on vehicles for planetary exploration may be more similar to automotive applications, on which much research is being conducted, than to space applications. Problems like reliability, working in conditions with quickly varying power request, reduced maintenance and mechanical stress due to traveling on uneven ground are similar, but the requirement of low cost that makes everything more difficult in vehicular applications is much less severe.

8.4 Electrochemical Batteries

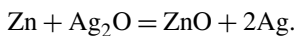
8.4.1 Primary Batteries

The electrochemical batteries that have the highest energy density are primary, i.e. non rechargeable, batteries. Even the common alkaline batteries have an energy density of 130 Wh/kg, while lithium batteries reach 300 Wh/kg and zinc-air ones 310. The main overall characteristics of primary batteries are listed in Table 8.4. The values of the energy density (referred to the mass and volume) are just orders of magnitude, since they depend on the exact type and make of the battery and also on the working conditions. The cell voltage reported is that of the fully charged battery while not generating current.

Primary batteries can, however, be used only for very short duration or for particular applications. Since some of them have a limited self-discharge, it is possible to use primary batteries for devices that must remain in standby for long times (even tens of years) using almost no power and then send a signal when an event takes place.

Among primary cells it is possible to mention

- Zinc–carbon cells. They are the oldest and cheapest type of primary batteries, however, now they are obsolete and find little application in the aerospace field.
- Alkaline cells. They are not much different from zinc–carbon cells, since are based on a zinc anode and a manganese dioxide cathode with a potassium hydroxide electrolyte. Their good performance and low cost make them the most widely used type of general purpose non-rechargeable battery.
- Mercury batteries. They were used in the past, but their potential pollution hazard, due to the mercury content, made them to be banned.
- Silver–zinc batteries. They are among the most used in the aerospace field and contributed substantially to the *Apollo* missions: they were installed on the *Saturn* rocket, the command module, the LEM, the LRV and, after the *Apollo 13* accident, also on the service module. The chemical reaction powering the cell is



Silver is reduced at the cathode and the reaction occurs in a potassium hydroxide or sodium hydroxide electrolyte. Until 2004 they contained a small quantity of

Table 8.4 Main characteristics of primary batteries (e/m : mass energy, e/v : volume energy density)

Type	e/m (Wh/kg)	e/v (Wh/dm ³)	Cell voltage (V)
Zinc–carbon	75	100	1.5
Mercury	120	–	1.35
Alkaline	130	320	1.5
Silver–zinc	130	500	1.8
Lithium	280–350	300–700	2.8–3.8
Zinc–air	310	1000	1.4

mercury (about 0.2%) to prevent corrosion of the anode, but the most modern types are free from this pollutant.

Their energy density is similar to that of alkaline cells, but their discharge curve is flatter. They are currently available in many sizes, mainly small button type cells, but larger sizes are available.

- **Lithium cells.** The general term lithium batteries indicates a wide family of different types of batteries, working on different chemistries. They have generally high energy densities and high cell voltage, but their performance and cost vary. The most common on the market are those based on a metallic lithium anode and manganese dioxide cathode. The mass energy density is about 280 Wh/kg, the volume energy density is 580 Wh/dm³, the nominal voltage is 3 V and the open circuit voltage is 3.3 V. They are suitable for low-drain, long-life, low-cost applications. They have also a wide temperature range.

On the other side, lithium thionyl chloride (the thionyl chlorate constitutes the liquid cathode) are much more costly, difficult or dangerous to operate but have extremely high performance that can reach even 500 Wh/kg, which is the highest energy density for any battery type. The high energy density and good low-temperature characteristics make them suitable for some space applications, even if the types with higher energy density supply lower discharge currents. Also lithium–carbon monofluoride cells are used in aerospace applications.

In general, lithium batteries may be discharged very quickly producing large currents. This can be exploited in some cases, but can also constitute a danger when accidentally shorted, since the ensuing overheating may lead to explosion of the cell.

- **Zinc–air batteries.** They work by oxidizing zinc with oxygen from the air; as such they are similar to fuel cells. Since they depend on air, they are not usable in space except if air (or directly oxygen) is carried on board. They have been used on Earth to power electric vehicles and theoretically may be used to power rovers and robots.

Each cell can be modeled, from the electrical viewpoint, as a circuit made by an ideal voltage generator with a resistor, modeling the internal resistance of the cell,

in parallel, even if more complex models in which also capacitors and inductors are included, can be found in the literature. The value of the internal resistance of the cell varies with many parameters, including the state of charge, the current, the temperature, etc.

During the discharge the voltage at the terminals of the cells decreases. The plot of the voltage as a function of time is referred to as the discharge characteristics of the cell. Initially there is a sharp drop from the maximum voltage, typical of the fully charged state, to a lower value that is maintained, with a slight decrease, for most of the discharge time. When the discharged conditions are approached there is a sharp drop again. The discharge curve is much influenced by how fast the discharge is: if the current is large the voltage decrease in the intermediate phase may be larger, depending on the battery type.

8.4.2 Secondary (Rechargeable) Batteries

Battery operated vehicles and robots that must be used for anything but a short time must use rechargeable (secondary) batteries that can be recharged either from the power system of the robot or rover itself (e.g. solar cells) when the device is not used or when it requires less power than the primary power source can supply. The batteries can also be recharged from a fixed power plant, located on the lander or at an outpost.

Conceptually, secondary battery are similar to primary batteries but for the fact that the chemical reaction is reversible and can be run backwards by passing a current through the cell. However, this reversibility is never complete, and the battery cannot be recharged an infinite number of times: at every recharge the performance of the energy conversion somewhat deteriorates until the cell cannot be recharged any more.

The performance of all batteries depend on many factors and, above all, its capacity is affected by how fast the charge and discharge process is performed.

The latter effect is expressed by the Peukert's Law, introduced by W. Peukert in 1897 for lead–acid batteries,

$$C = i^k t, \quad (8.1)$$

where C is the capacity of the cell at a one-ampère discharge rate, i is the discharge current, k is the nondimensional Peukert constant and t is the time of discharge. For lead–acid batteries, the value of k is about 1.3, with lower values for gel batteries and higher ones for liquid electrolyte cells.

Given the nominal capacity of a battery, a charge is said to be performed at a rate C if the charging current in A is equal to the capacity expressed in Ah (Ampère hours). If the charging efficiency had a unit value, this would imply that the charge phase would last 1 hour; in practice for most batteries the charging time at a rate C is about 1.2 hours. The nominal capacity of a battery is usually determined by discharging in 20 hours ($C/20$) at a temperature of 20°C.

Usually slow charging is defined as charging at a rate lower than C . For instance, accounting for the charging efficiency, a slow charge rate $C/3$ leads to a charging time of about 4 hours. Most batteries can withstand indefinitely a very low charge rate (usually said trickle charging), below $C/10$. Fast charging, i.e. charging in less than one hour (rate greater than $1.2C$) requires precautions and may spoil some types of batteries. The more advanced types of batteries are able to be charged quickly, even with rates greater than $10C$.

In a similar way, also fast discharging may be detrimental to the life and performance of the battery. Even in case of batteries able to be charged quickly, the capacity and the energetic efficiency decrease with increasing charge and discharge current.

The energy density of the battery of a robot or a rover thus depends on whether recharging is performed between one mission and the other or the rover has a low power generator (a solar panel, for instance) and the batteries are continuously kept charged and used when the required power exceeds the power generated by the primary source or when for some reason the primary source is off (e.g. the solar panel is in the shade).

Generally speaking, batteries cannot be used at the same time at high power density and at high energy density: as already stated, when required to supply high power (discharge with high current) the efficiency, and consequently the capacity, decreases. They show also a reduction of the useful life when used in these conditions.

Lead–acid batteries are particularly sensitive to this, while some kinds of nickel–cadmium and other more advanced batteries can operate with high currents, both during charging (quick charge) and during discharge (high power output).

An ideal battery should be characterized by

- High energy density,
- Almost constant voltage during discharge (a flat discharge characteristics),
- Low internal resistance,
- High discharge current,
- Possibility of operating at both high and low temperatures,
- Long operating life and high number of charge–discharge cycles,
- High efficiency in recharge,
- Low cost.

No actual battery is particularly good in several of these points.

The voltage of a secondary battery decreases during discharge in a way that is similar to that of primary cells. Since the life of the cell is not over once it is discharged, the third phase of the discharge curve must not be used: too deep discharges are detrimental to the possibility of fully recharging the battery and can, in the long run, deteriorate it. The discharge curves of some secondary batteries are reported in Fig. 8.2.

Fig. 8.2 Discharge curves of some rechargeable batteries (slow discharge)

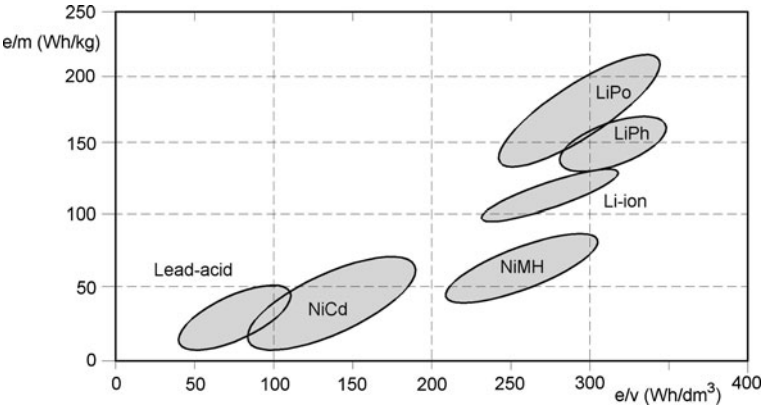
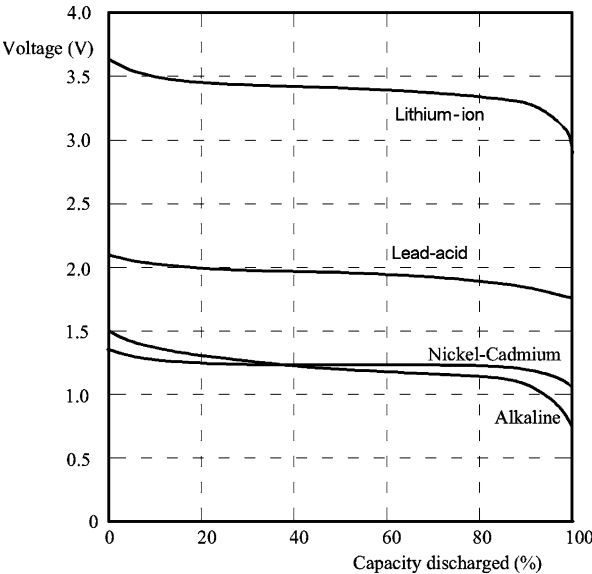


Fig. 8.3 Mass and volume energy density for the main types of secondary batteries

The main characteristics of some types of secondary batteries are reported in Table 8.5; a plot of the mass energy density versus the volume energy density is reported in Fig. 8.3.

The main types of secondary cells are:

- **Lead–acid cells.** They are the most common type of secondary batteries. While in origin they were based on an open container full of electrolyte (sulfuric acid), more modern type are sealed and provided with a valve to prevent pressure built up. The electrolyte can be semi-solid (gel) or can be absorbed in a special fiber-glass matting.

Table 8.5 Main characteristics of some types of secondary batteries (e/m : mass energy density, e/v volume energy density, P/m : power density, V : cell voltage, η : charge/discharge efficiency, d : self-discharge, c : number of cycles)

Type	e/m (Wh/kg)	e/v (Wh/dm ³)	P/m (W/kg)	V (V)	η (%)	d (%/month)	c
Lead–acid	30–40	60–70	180	2.0	70–92	3–4	500–800
NiCd	40–60	50–150	150	1.2	70–90	20	1,500
NiFe	50	–	100	1.2	65	20–40	–
NiZn	60	170	900	1.2	–	–	100–500
NiMh	30–80	140–300	250–1,000	1.2	66	30	500–1,000
Alkaline	85	250	50	1.5	99	<0.3	100–1,000
Li-ion	150–250	250–360	1,800	3.6	80–90	5–10	1,200
LiPo	130–200	300	3,000	3.7	–	2.8–5	500–1,000
LiPh	80–12	170	1,400	3.25	–	0.7–3	2,000
LiS	400	350	–	–	–	–	100

- Nickel-based cells. A wide family of rechargeable batteries are based on nickel chemistry, like are nickel–cadmium (NiCd),² nickel–iron (NiFe), nickel–zinc (NiZn), nickel metal hydride (NiMh).
- Rechargeable alkaline cells.
- Lithium-based cells. They include lithium–ion (Li-ion), lithium ion–polymer (LiPo), lithium–iron–phosphate (LiPh) and lithium–sulfur (LiS) cells.

As a general consideration, nickel-based batteries have a larger self-discharge, while lithium batteries are better from the viewpoint of quick charging and discharging. The highest energy density is obtained from lithium–sulfur cells, which, however, have a short life in terms of cycles.

The charge phase of any battery system is critical, since the efficiency and the life of a battery depends on how accurately the energy is introduced into the system. Some batteries are less critical from this viewpoint, like lead–acid and NiCd cells, although the latter display what is usually referred to as a memory effect, consisting in the tendency to lose some of the capacity when recharged repeatedly after being only partially discharged.

Advanced batteries are more critical, and may even become dangerous if not properly charged, with the risk of fire and explosions. This is solved by using accurately controlled, microprocessor-based, chargers. Battery packs are increasingly provided with on-board electronics that monitors continuously the charge conditions and keeps the current flowing through the various cells under control.

Since the voltage varies during the discharge phase according to the charge state of the battery, robots and vehicles powered by batteries are usually provided with a

²Actually NiCd is a proprietary name and should not be used to indicate nickel–cadmium cells in general.

voltage regulator. Other problems are due to the presence of both logical elements and power components close by and possibly connected to the same circuit. The latter can produce noise and electromagnetic interference that must be kept under control to ensure proper operation of the system. The electric and electronic circuitry of the robot must be designed with extreme care, to ensure a good power efficiency and at the same time a low level of noise.

Finally, when the batteries have to supply (or to receive) high power peaks for a short time it might be expedient to supplement the battery system with an auxiliary energy storage device able to operate under these extreme conditions without problems. Supercapacitors and flywheels are well suited for this task (see below).

8.5 Other Energy Storage Devices

Energy can be stored in several forms on board vehicles or rovers. In case of stationary plants, it is possible to store energy in the form of potential energy, a thing that is commonly done in pumped basins, where water is pumped when the generation capacity is higher than the needs, and then returned to a lower level when energy is needed. This, however, requires a gravitational field, which is available only on the surface of a planet, the presence of a fluid, possibly in liquid form, and large investments. While being not impossible to think of storing energy on Titan by pumping methane in a suitable basin located at a higher level, this would be practical only in a hypothetical future when large civil engineering works will be performed there.

Several schemes have been proposed, and sometimes implemented, to store energy on board vehicles on Earth. They include elastic potential energy in both a compressed gas or a deformed solid, kinetic energy in a flywheel, electric energy in a capacitor, magnetic energy in an inductor, or thermal energy in objects having a large thermal capacity.

Two storage devices will be mentioned here: supercapacitors and flywheels.

8.5.1 Supercapacitors

A supercapacitor is essentially a capacitor whose capacitance, for its size and mass, is much larger (by orders of magnitude) than that of standard capacitors. Actually, supercapacitors have been defined as an intermediate technology between capacitors and electrochemical batteries.

Their discharge curve is, however, linear, since the voltage at their terminals is proportional to the charge stored. There is thus a strong drop of voltage during discharge, which in most applications compels to use a voltage regulator.

At present, the energy density of supercapacitors is between 1 and 10 Wh/kg, with peak values up to 30 Wh/kg, while the power density can be as high as 5,000 Wh/kg. The largest units built have a capacitance of 5,000 F. Although being much inferior to batteries for what their energy density is concerned, they have

an extremely high power density, since they can be charged and discharged in a short time.

Supercapacitors are thus ideally suited to perform as energy buffers for batteries, supplying and accepting sharp current peaks.

8.5.2 *Flywheels*

Energy can be stored in a rotating object in the form of kinetic energy. The velocity Ω of a flywheel with moment of inertia J is linked with the energy stored e by the obvious relationship

$$e = \frac{1}{2} J \Omega^2, \quad (8.2)$$

showing that the speed variations during the charge and discharge are large. This implies the presence of a power interface that can be a rotary actuator (like an electrical motor/generator or a hydraulic motor/pump) able to operate at variable speed or of a variable ratio mechanical transmission.

The energy density of the flywheel itself may be from 10 Wh/kg to even 100 Wh/kg, but if the whole system is accounted for, these figures are much lower. The high power density allows flywheels to be used as power buffers, like supercapacitors.